SOIL AND ROCK CAUSING ENGINEERING GEOLOGIC PROBLEMS IN UTAH

by
William E. Mulvey
Utah Geological Survey

SPECIAL STUDY 80 **1992**
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

Mulvey SOIL AND ROCK CAUSING ENGINEERING GEOLOGIC PROBLEMS IN UTAH UGS Special Study 80 1992

UTAH GEOLOGICAL SURVEY
2363 South Foothill Drive
Salt Lake City, Utah 84109-1491

THE UTAH GEOLOGICAL SURVEY is organized into three geologic programs with Administration, Editorial, and Computer Resources providing necessary support to the programs. The ECONOMIC GEOLOGY PROGRAM undertakes studies to identify coal, geothermal, uranium, hydrocarbon, and industrial and metallic mineral resources; to initiate detailed studies of the above resources including mining district and field studies; to develop computerized resource data bases; to answer state, federal, and industry requests for information; and to encourage the prudent development of Utah's geologic resources. The APPLIED GEOLOGY PROGRAM responds to requests from local and state governmental entities for engineering geologic investigations; and identifies, documents, and interprets Utah's geologic hazards. The GEOLOGIC MAPPING PROGRAM maps the bedrock and surficial geology of the state at a regional scale by county and at a more detailed scale by quadrangle. Information Geologists answer inquiries from the public and provide information about Utah's geology in a non-technical format.

THE UGS manages a library which is open to the public and contains many reference works on Utah geology and many unpublished documents on aspects of Utah geology by UGS staff and others. The UGS has begun several computer data bases with information on mineral and energy resources, geologic hazards, stratigraphic sections, and bibliographic references. Most files may be viewed by using the UGS Library. The UGS also manages a sample library which contains core, cuttings, and soil samples from mineral and petroleum drill holes and engineering geology investigations. Samples may be viewed at the Sample Library or requested as a loan for outside study.

The UGS publishes the results of its investigations in the form of maps, reports, and compilations of data that are accessible to the public. For information on UGS publications, contact the UGS Sales Office, 2363 South Foothill Drive, Salt Lake City, Utah 84109-1491, (801) 467-7970.

CONTENTS

Abstract 1
Introduction 2
Methods and Scope 2
Problem Soil and Rock 2
    Expansive Soil and Rock 2
    Collapsible Soil 5
    Gypsiferous Soil and Rock 5
    Limestone and Karst Terrain 6
    Soils Subject to Piping 8
    Sand Dunes 9
    Peat 11
Other Problems 12
    Mine Subsidence 12
    Sodium Sulfate 13
Conclusions and Recommendations 13
Acknowledgments 14
Selected References 14
Appendix 15

ILLUSTRATIONS

Figure 1. Schematic diagram of water absorption processes in clay minerals 3
Figure 2. "Popcorn" texture on surface of expansive soil 3
Figure 3. A, Damage to foundation at Moab Airport due to expansive soils, and B, building damage caused by expansive soils in Green River area 4
Figure 4. Surfacing effluent from wastewater disposal system due to reduction of permeability and plugging by expansive soils 4
Figure 5. Damage to building in Nephi due to collapsible soil 6
Figure 6. Collapse of surface due to dissolution of underlying gypsum in rock near Vernal, Utah 7
Figure 7. Schematic cross section of typical karst terrain showing geology and hydrology 7
Figure 8. Karst sinkhole in the channel of the Virgin River 8
Figure 9. Schematic cross section of pipe in Holocene alluvium 9
Figure 10. A, Pipe in road surface over Holocene alluvium along the drainage of Montezuma Creek in San Juan County, Utah, and B, pipe exiting stream bank 10
Figure 11. Coral Pink sand dunes (silica) in Kane County, Utah 10
Figure 12. Gypsum dunes in the Great Salt Lake Desert 11
Figure 13. Oolitic dunes covering roads at Antelope Island State Park 12
Figure 14. Schematic cross section of surface subsidence caused by collapse of underground mine workings 12
Figure 15. Sodium sulfate-rich ground-water seeps in the Green River Formation, near Duchesne, Utah 13
Plate 1. Soil and rock causing problems . . . . . in pocket

APPENDIX

Appendix 1. Geologic time scale 16
Appendix 2. Quadrant designations and geologic units causing engineering geologic problems in Utah 17
Appendix 3. List of references used to compile the map 19

SOIL AND ROCK CAUSING ENGINEERING GEOLOGIC PROBLEMS IN UTAH

by

William E. Mulvey
Utah Geological Survey

ABSTRACT

Soil- and rock-related engineering geologic problems occur in a variety of geologic settings and are some of the most widespread and costly geologic hazards in Utah. To show the distribution of problem soil and rock, a statewide map (1:500,000 scale) was compiled documenting the occurrence of problems related to soil and rock as well as geologic units with the potential to cause similar problems. The map is designed to alert developers, planners, engineers, and others of potential problem areas where more detailed geotechnical studies should be performed prior to development. Information for the map was obtained from local, state, and federal government investigations and private consultants' reports.

Nine types of problems related to soil and rock are shown. Of all the problem deposits depicted on the map, the most extensive are expansive soil and the rock units from which it is derived. Expansive soil and parent rock occur over approximately 15 percent of the state. The majority of expansive soil problems are related to weathered marine shales in southern Utah, and Lake Bonneville and other deep-lake sediments in central basin areas of western Utah. Subsidence of the ground surface due to collapsible soil has caused extensive damage in many parts of the state. Collapsible or hydrocompactible soil is common in Holocene alluvial-fan and debris-flow deposits in Utah. Soil and rock containing high concentrations of gypsum are susceptible to dissolution and subsidence.

Another rock with the potential to cause problems is limestone. Limestone susceptible to solution and subsidence occurs in northern Utah, the Uinta Mountains, and mountains of the western deserts, where karst topography is locally well developed. No known damage to structures in Utah has occurred from ground collapse or subsidence related to karst, but because karst ground-water systems have little filtering capacity, contamination of ground water is a major concern. Piping is a common problem in fine-grained Holocene alluvium incised by streams in much of southeastern Utah. Collapse of soil pipes and subsequent erosion has damaged roads and agricultural land.

The four remaining problem deposits are more localized in their distribution. Sand dunes with a variety of compositions occur in isolated patches throughout western Utah, and actively migrating dunes can cause road maintenance problems. Along the shores of Great Salt Lake, Utah Lake, and in glaciated drainages in the mountains, peat deposits are susceptible to oxidation, desiccation, and subsidence when exposed to the air or when drained. On the eastern slope of the Wasatch Plateau, along the Book Cliffs, and in the Park City and Tintic mining districts, surface subsidence due to collapse of underground mine workings may occur. Western Utah has extensive areas of sodium sulfate-rich soils which can damage structures.

INTRODUCTION

Geologic materials with characteristics that make them susceptible to volumetric changes, collapse, subsidence, or other engineering-geologic problems are referred to as problem soils and rocks. Geologic and climatic conditions in much of Utah provide a variety of localized to widespread occurrences of these materials. This map and accompanying text delineate and describe known areas of problem soil and rock in Utah. The report is intended to provide a guide to areas where hazards from these materials may be expected.

Nine types of problem soil and rock are included on the map and are discussed in the text. They are: 1) expansive soil and rock with high shrink/swell potential, 2) collapsible or hydrocompactible soil, 3) gypsum and gypsiferous soil susceptible to dissolution, 4) limestone susceptible to solution under some hydrogeologic conditions, 5) soil subject to piping (localized subsurface erosion), 6) active dunes, 7) highly compressible peat, subject to volume change, 8) underground mines which may subside and collapse, and 9) soil containing sodium sulfate. Some materials, such as expansive soil and limestone, cover large areas of the state, whereas others, like dunes and peat, are of limited areal extent.

Geology and climate are the main factors which influence the distribution of problem soil and rock. The geologic parent material largely determines the type of problem present. For example, expansive soil is most often associated with shale, and karst dissolution features form in limestone and gypsiferous formations. Weathering and erosion are controlled by local and regional climate. A prime example of the influence of climate is collapsible soils, which are found predominantly in arid regions where annual rainfall is low.

Humans have no influence on the distribution of problem soil and rock, but human activities are often adversely affected by them and many urbanized areas in the state are susceptible to damage from these deposits. As development encroaches on less suitable terrain, damage from problem soil and rock has increased. This statewide compilation of available information indicates areas where detailed geotechnical studies may be needed to identify and mitigate problem soil and rock hazards, and thus avoid costly corrective measures.

METHODS AND SCOPE

The map and text are compiled from investigations conducted in Utah by numerous agencies and authors. A limited number of aerial photographs were used to verify data; due to the large area covered, field work was confined to critical areas.

Two types of information are shown on the map: 1) documented occurrences of problem soil and rock, commonly causing damage to structures, and 2) geologic units with potential to cause similar kinds of problems. Documented occurrences provide the basic information used to identify problem geologic units. Deposits with the potential to cause damage are more widespread than documented occurrences, which are clustered in urban areas where problem soil and rock are encountered by development. Available data concerning problem materials consist primarily of unpublished consultants' reports, and state, local, and federal government investigations. Most documented occurrences are limited to instances of damage to structures and roads. In some cases, however, soil tests were used to document occurrences. Although this type of data does not represent actual damage to a structure, it does indicate the potential for damage to occur.

Due to the small scale of the map, areas affected by karst, dunes, and expansive soils are generalized. These areas are widely distributed throughout the state, and the largest and best known deposits were mapped. There may be localized problem areas not depicted due to the map scale. This is especially true of many small areas of active dunes which are scattered throughout the state.

PROBLEM SOIL AND ROCK

The various categories of problem soil and rock are discussed according to the processes that created the deposits, their distribution within Utah, their associated engineering-geologic problems and geologic hazards, and the mitigation techniques used to reduce the hazards. Specific problem deposits and their locations are shown on the map and are listed in the table in appendix 2.

Expansive Soil and Rock

Expansive soil and rock are the most common problem deposits in Utah, covering approximately 15 percent of the state. Most expansive soil and rock were originally deposited as clay, silt, and some salt in seas or lakes that covered much of the state at different times in the geologic past. Expansive deposits are typically clay-rich. The clay minerals cause the deposits to expand and contract with changes in moisture content. All clay minerals expand to some degree, but the most common clay mineral associated with expansive deposits in Utah is montmorillonite (Bauman, 1964).

Some varieties of montmorillonite can swell to 2,000 times their original dry volume (Tourtelot, 1974). Clays may swell in two ways when wetted, either by absorption of water between clay particles or by absorption of water into the crystal lattice that makes up the individual particles (figure 1). In both processes, the absorbed water causes the soil or rock to expand. Montmorillonite commonly swells by absorption of water be-

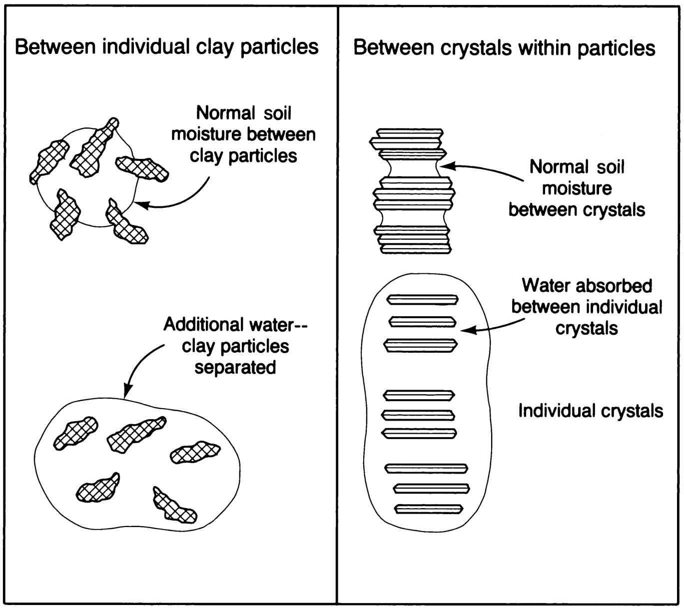


Figure 1. Schematic diagram of water absorption processes in clay minerals.

Figure 2. "Popcorn" texture on surface of expansive soil (photo by G. E. Christenson).

tween individual crystals. Costa and Baker (1981) state that uplift pressures in undisturbed montmorillonitic clays can range from 3,000 to 11,200 lbs/ft^2 (14,646 to 54,678 kg/m^2). Pressures this great may exceed foundation loads imposed by single-family homes, single-story buildings, roads, sidewalks, and concrete slabs. As the material dries, the loss of water causes it to shrink. The processes of wetting and drying and freeze-thaw churn and disturb the surface of expansive deposits, giving some of them a characteristic "popcorn" texture. This texture is a good indicator of the presence of expansive soil and rock, and it can be seen in many areas of the state (figure 2).

Mesozoic-age marine shales are some of the most widely exposed rocks in the state and typically contain high concentrations of montmorillonite clay. They are the source of most expansive deposits in Utah, particularly in the southeastern part of the state (appendices 2, 3). Structures in Price, Green River, Vernal, and St. George built on these shales have suffered extensive damage. These same shales are also found in narrow outcrop bands along the north and south flanks of the Uinta Mountains. In addition to marine shales, fine-grained Lake Bonneville deposits and other deep-lake sediments in the western basins, and volcanic tuff in the north-central part of the state are susceptible to shrinking and swelling. The extent of expansive Lake Bonneville sediments in the central basins of western Utah is unknown. However, geotechnical studies show that Bonneville deposits northeast of Delta and in central and eastern Tooele County are expansive. Expansive volcanic tuff in Morgan, Davis, and Summit Counties is known to have damaged structures. In the town of Mountain Green in Morgan County, damage from expansive soil caused several homes to be condemned and removed. In all of these areas, improperly designed roads and structures are susceptible to damage from expansive soil.

Problems commonly associated with expansive soil and rock are cracked foundations (figure 3), heaving and cracking of road surfaces, and failure of wastewater disposal systems. Single-family homes are particularly susceptible to expansive soil and rock because foundation loads (1,500 to 2,500 lbs/ft^2; 7,323 to 12,205 kg/m^2) may be less than the expansive pressures (3,000 to 11,200 lbs/ft^2; 14,646 to 54,678 kg/m^2) caused by the swelling material, making structures subject to heave (Costa and Baker, 1981). Larger, heavier buildings are better able to withstand the expansive pressure and are less susceptible. Sidewalks, roads, buried utilities, and slabs-on-grade are also susceptible to cracking and damage due to differential expansion of underlying material.

Wastewater disposal systems using soil-absorption fields can also be damaged by expansive soil. Clay-rich deposits develop cracks when dry, leaving voids which allow large volumes of water to infiltrate initially. Once saturated, the clay minerals swell, closing the voids. Soil-absorption systems installed in expansive soil work until the soil becomes saturated and begins to swell. The soil quickly becomes impermeable and the systems clog and fail, causing wastewater to flow to the surface creating a health hazard (figure 4).

Drainage conditions affecting soil moisture content are important in areas of expansive soil. When water from sprinkler systems or runoff from roofs and roads reaches deposits

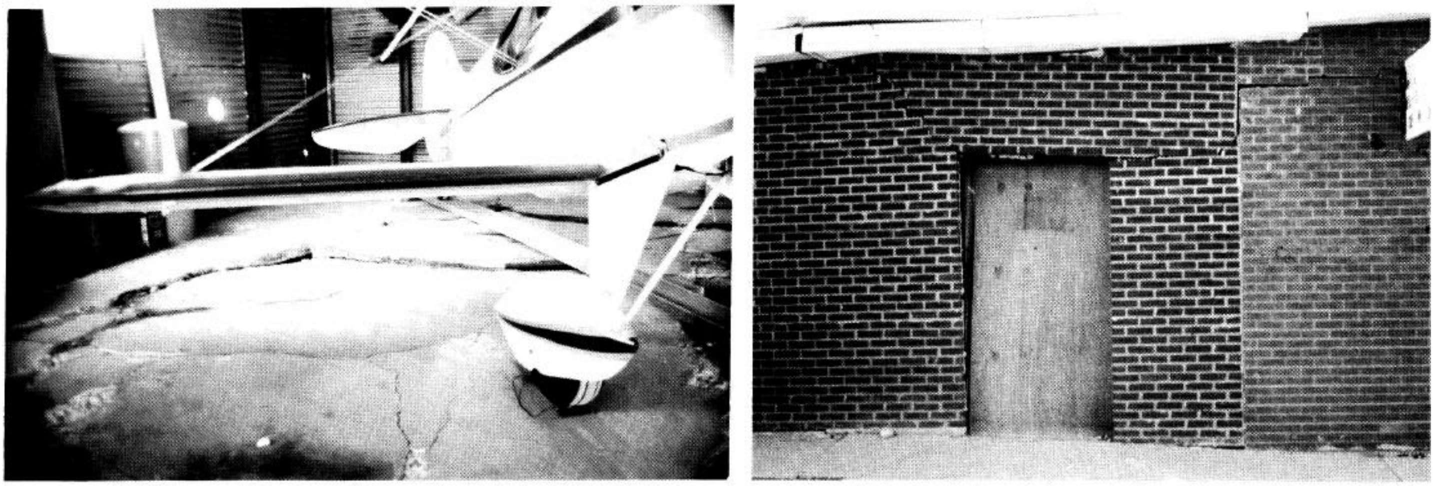


Figure 3. A, Damage to foundation at Moab Airport due to expansive soils, and B, building damage caused by expansive soils in Green River area (photo W.R. Lund).

Figure 4. Surfacing effluent from wastewater disposal system due to reduction of permeability and plugging by expansive soils (photo W.R. Lund).

beneath the structure, damage may occur as the material changes volume. To mitigate and reduce damage resulting from improper drainage or foundation design, several techniques can be used, Gutters and downspouts should direct water at least 10 feet (3m) away from foundation slabs (Costa and Baker, 1981). Any vegetation that concentrates or draws large amounts of water from the soil should not be used in landscape designs near foundations. Areas of the home such as floors or walls near heating or cooling units should be insulated to prevent evaporation, which may cause local changes in soil moisture. House foundations can be strengthened by reinforcing the concrete with steel bars. Walls can be supported by pilings driven into the soil to a depth below the active zone (Costa and Baker, 1981). Wide shoulders and good drainage along highways can prevent road damage. In highway foundations a combination of hydrated lime, cement, and organic compounds can be added to road subgrade materials to stabilize the underlying soil (Costa and Baker, 1981). If the presence of expansive soils is suspected, a 24-hour "presoak" of the material before determining percolation rates for wastewater disposal systems can reduce the potential for system failure.

Collapsible Soil

The phenomenon of hydrocompaction, which causes subsidence in collapse-prone soil, occurs in loose, dry, low-density deposits, which decrease in volume or collapse when saturated for the first time since deposition (Costa and Baker, 1981). Collapsible soils are geologically young materials, such as Holocene-age alluvial-fan and debris-flow sediments, and some wind-blown silts. These deposits have a loose, "honeycomb" structure and high dry strength, resulting from rapid deposition and drying. When saturated, the "honeycomb" structure collapses and the ground surface subsides, damaging property and structures.

Alluvial-fan deposits are the most susceptible materials for hydrocompaction in Utah. Fans commonly have steep surface gradients, allowing rapid runoff of surface water during fan-building depositional events. This allows deposits to dry quickly and retain a relatively low density. The sediments are commonly covered by similar material from subsequent depositional events creating a thick sequence of collapse-prone material. Collapsible soils have a high dry strength resulting from the bonding produced by dry clay films and soluble minerals on or between particles. Between the particles are voids formed by air entrapped in the sediments at the time of deposition. Hydrocompaction is generally initiated by human activities that involve applying water to the deposit such as irrigation, water impoundment, lawn watering, alterations to natural drainage, or wastewater disposal. The water wets the susceptible materials, weakening the bonds between particles and reducing the strength of the material, which causes it to collapse and subside.

Field identification of hydrocompactible deposits is difficult, however, most are classified as sandy silt (ML) or silty sand (SM) in the Unified Soil Classification System. In general, though, soil thought to be susceptible to hydrocompaction should be tested in the laboratory for positive identification. Costa and Baker (1981) outline four conditions as conducive to the development of hydrocompactible soils: (1) High void ratio - materials with bulk dry densities less than 1.3 g/cm^3 (80 lb/ft^3) are subject to large amounts of settlement. Bulk densities greater than 1.4 g/cm^3 (90 lb/ft^3) generally have less settlement. (2) Clay content of about 12 percent - if deposits contain more than this amount of clay, swelling of the clay generally reduces the amount of subsidence. Deposits with less than 12 percent clay do not have enough clay to provide intergrain bonds that maintain a large void ratio. (3) Predominant clay mineral is montmorillonite, which becomes hard when dry and acts as a strong binder. (4) Deposit should be dry.

Collapsible soil is present in southwestern Utah, particularly near the Cedar City and Hurricane Cliffs area, and around Richfield and Monroe in south-central Utah. In Cedar City, approximately 3 million dollars in damage to public and private structures has been attributed to collapsible soil (Kaliser, 1978). Elsewhere in Utah, areas most susceptible commonly occur along any mountain front where alluvial-fan deposits contain fine-grained deposits derived from shales, mudstones, and possibly volcanic rocks. Climate is also critical to the development of hydrocompactible soil. The drier areas of Utah such as the Great Basin and Colorado Plateau, where rainfall seldom penetrates below the root zone (annual precipitation of 9 to 15 inches; 23-38 cm), provide the best conditions for development of hydrocompactible soil.

Damage and problems associated with collapsible soil all relate to the introduction of water (usually by man) into the soil in greater amounts than the average annual precipitation. This excess leads to eventual collapse of the soil (figure 5). Collapse of the soil structure causes differential settlement, damaging structures. Landscaping requiring irrigation is the most common reason for application of additional water. The soil around structures is wetted to a depth below that reached by rainfall, destroying the bonding between grains, and collapse occurs. Collapse may also occur due to crop irrigation, concentrated runoff from paved surfaces, and water introduced into the subsurface by wastewater disposal systems.

The most common procedure to detect and avoid collapsible soils is a soil consolidation test. If collapsible soils are discovered at a site several methods can be used to reduce the potential for damage. Most are expensive and lengthy. The building site can be deeply wetted and compacted to densities that will support the building. Building sites can also be over-excavated and backfilled with suitable material, and runoff collection or landscaping designed to direct water away from the structure. Avoiding areas containing collapsible soils is the least expensive and best mitigation method.

Gypsiferous Soil and Rock

Gypsiferous deposits are subject to settlement caused by dissolution of gypsum, creating a loss of internal structure and volume within the deposit. Gypsum is a primary component in some rocks and in soils derived form those rocks. Gypsum-rich soil may also be formed in two other ways, as a secondary mineral deposit leached from surficial layers and concentrated lower in the soil profile, or as a material transported by wind or water from outside sources. The most common sources for airborne gypsum are playas, on which crusts of gypsum salts are formed as the wetted playa surface dries during the warmer months of the year. These crusts of gypsum are easily eroded and transported by wind.

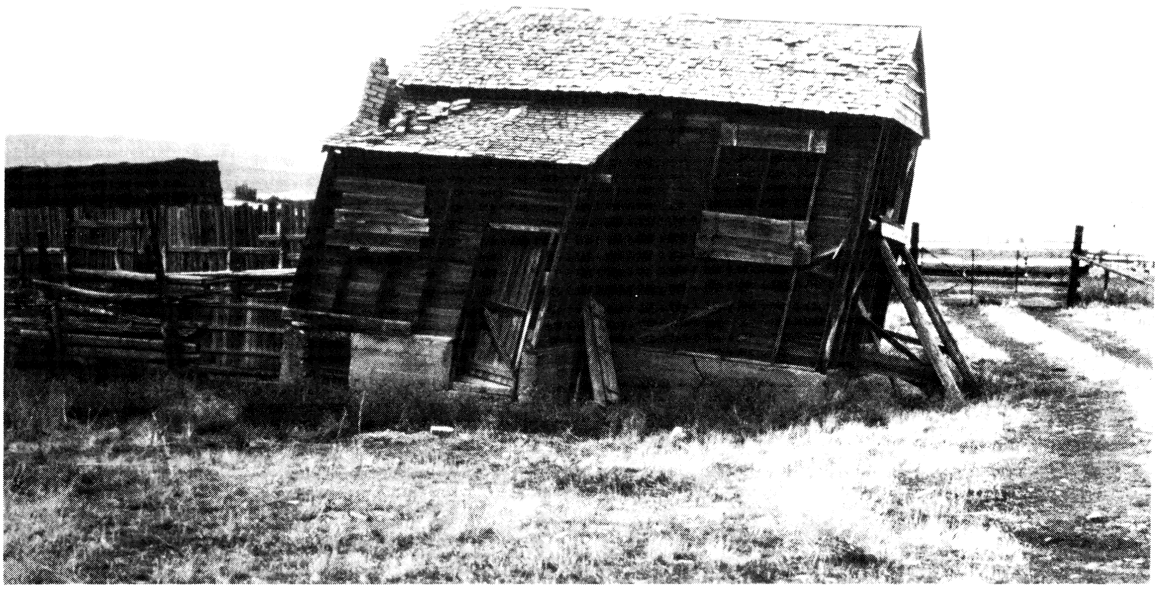


Figure 5. Damage to building in Nephi due to collapsible soil (photo G.E. Christenson).

Gypsiferous rock and soil deposits are common in southwestern Utah, particularly along the base of the Hurricane Cliffs, and in the Uinta Basin near Vernal. There and elsewhere in southwestern Utah, much of the gypsum present is derived from erosion of gypsum-rich rock.

Gypsiferous rock and soil deposits have the potential to cause damage to foundations and to cause land subsidence and sinkholes. When wetted by irrigation for crops or landscaping, or by water from wastewater disposal systems, gypsiferous soil may subside due to dissolution of gypsum. In some cases large underground solution cavities may form and then collapse (figure 6). Gypsum is also a weak material with low bearing strength. When gypsum weathers it forms sulfuric acid and sulphate (Bell, 1983). These compounds may react with certain types of cement, weakening foundations by damaging the exterior surface.

Damage to structures from gypsiferous soils can be limited by several methods. Soil tests to determine the presence of gypsum are a first step. If gypsum is present, the outer walls of structures can be coated with impermeable membranes or bituminous coatings to protect them from deterioration. Special types of concrete can also be used which resist damage from gypsum. Because gypsum is dissolved by contact with water, runoff from roofs and gutters should be directed away from the structure. Landscaping close to the house should not include plants which require regular watering.

Limestone and Karst Terrain

Karst is a geomorphic term that describes a type of terrain with drainage and relief features created by the dissolution of rock by ground and surface waters (Jennings, 1985) (figure 7). Karst terrain is characterized by closed depressions or "sinkholes," caverns, and underground drainage. The most common rock to develop karst terrain is limestone, but karst can also develop in dolomite and gypsum. Limestone is a common sedimentary rock and is composed largely of calcium carbonate ($CaCO_3$) in the form of the mineral calcite. Calcite has a solubility of 20 to 400 parts per million in water and is highly susceptible to dissolution. Dissolution removal of the rock by water is the process by which karst features are formed. Fractures within the rock, frost shattering, and stream erosion also aid in the development of karst landforms. Sinkholes, large caverns, and high fracture permeability of rock in karst regions commonly divert surface water underground.

Conditions for the development of karst terrain vary from region to region, but in general are controlled by several common factors. The type, frequency, and arrangement of planes of weakness within susceptible rock units are important because they affect permeability and hydrology in karst terrain (Jennings, 1985). Permeability controls dissolution activity. The potential for karst development is reduced if overlying deposits of unconsolidated material have a low pereability. This is especially true if the deposits consist of clay, which diverts or im-

Figure 6. Collapse of surface due to dissolution of underlying gypsum in rock near Vernal, Utah.

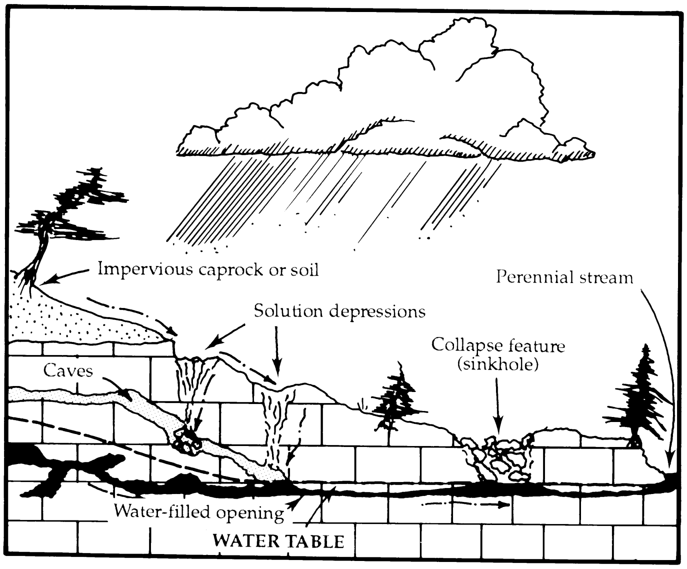


Figure 7. Schematic cross section of typical karst terrain showing geology and hydrology.

pedes water movement into the subsurface. Finally, time exerts great influence on the development of karst terrain. In general, large caverns take a long time to develop, but once present, the effects of collapse can appear quickly at the surface (Jammal, 1984).

Karst topography is present in middle Paleozoic-age (appendix 1) limestone and dolomite throughout northern and western Utah but is best developed in the Bear River Range and the northeastern portion of the state. South of the Bear River Range, sinkholes were present in the excavation for Porcupine Dam in Cache County and beneath a reservoir in Laketown Canyon in Rich County. Most karst features found in limestone and dolomite in the Great Basin of western Utah are relict features which may relate to moister climates during the Pleistocene, or may have been created by ground water prior to the rock being uplifted and tilted during basin and range normal faulting (F.D. Davis, Utah Geological Survey, oral communication, January, 1990). Relict features in the Kaibab Limestone along the Virgin River were exposed by recent flooding (figure 8). The potential for continued karst development in western Utah is low, except for areas where ground water is present in amounts large enough to cause dissolution of limestone and dolomite. In the northern part of the state, however, surface and ground water are more abundant and karst features are widespread and well developed. Aside from western and northern Utah, karst features are present on the north and south flanks of the Uinta Mountains and in the central Wasatch Range between Alpine and Spanish Fork Canyons. Karst features in all these areas directly affect surface and especially subsurface drainage and, because of this, play an important role in the type of geologic hazards present.

Karst terrain is particularly susceptible to ground-water pollution. The cavernous nature of karst terrain provides an avenue for contaminants from surface or subsurface sources to enter the local ground-water system. Once introduced, contaminants can spread rapidly due to the interconnected system of conduits. Contaminants remain concentrated, since the rock

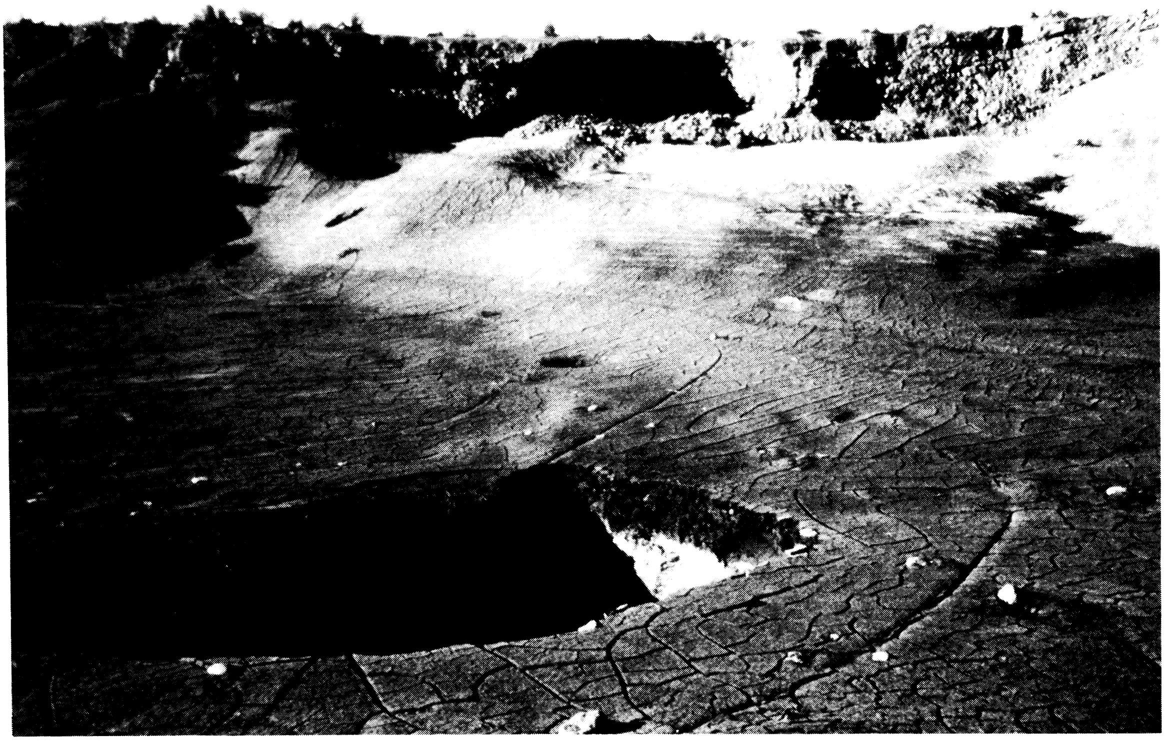


Figure 8. Karst sinkhole in the channel of the Virgin River (photo B.L. Everitt).

does not have the ability to filter impurities as soil or weathered rock does. Although pollution in karst areas has not been widely documented in Utah, other states such as Kentucky, Minnesota, and Florida have experienced ground-water pollution in karst terrain. In Utah, the most probable sources of contamination are wastewater disposal systems, landfills, and buried fuel storage tanks.

Cavernous, subterranean openings in karst terrain often collapse, leaving characteristic sinkholes at the surface. Structures built in such areas may be damaged by subsurface collapse. No documented occurrence of damage due to collapse has occurred in Utah, but the potential for damage exists in known karst areas. Avoiding areas underlain by limestone is the best method of preventing ground-water and collapse problems. If this is not possible, pre-construction planning and design of wastewater disposal systems based on thorough geologic and hydrologic investigations of construction sites can prevent ground-water pollution. Dams and other impoundments in limestone terrain require special design and mitigation considerations with respect to foundation stability and leakage.

Soils Subject to Piping

Piping is a common process in arid climates where fine-grained, uncemented, Holocene alluvium is incised by streams. The term piping describes subsurface erosion by ground water moving along permeable, noncohesive layers in unconsolidated materials and exiting at a free face that intersects the layer (Cooke and Warren, 1973; Costa and Baker, 1981). Removal of fine-grained particles (silt and clay) by this process creates voids that act as minute channels which direct the movement of water (figure 9). As channels enlarge, water moving through the conduit increases velocity and removes more material, forming a "pipe." The "pipe" becomes a preferred avenue for ground-water drainage, growing in size as larger volumes of water are intercepted. Increasing the size of the pipe removes support for its walls and roof, causing eventual collapse (figure 10). Collapse features form on the surface above the pipes, directing even more surface water into the pipes. Eventually, total collapse forms a gully that concentrates erosion along a line of interconnected collapse features.

Several conditions are necessary for piping. Most important

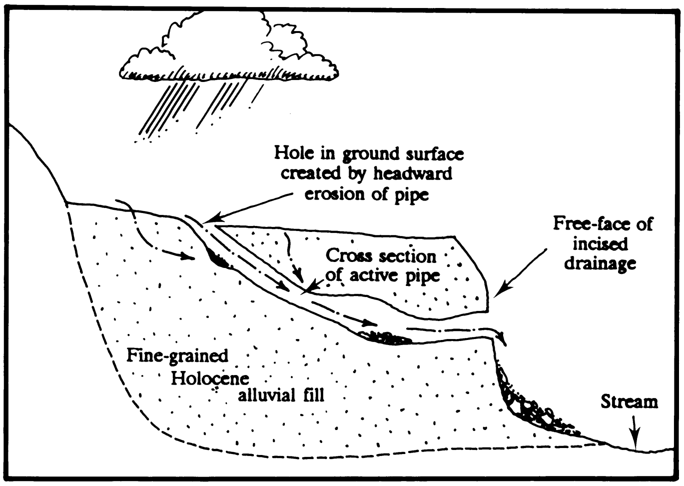


Figure 9. Schematic cross section of pipe in Holocene alluvium.

is water, present in volumes large enough to soak into the subsurface and reach layers or zones (animal burrows, decayed plant roots) which conduct the water to a free face. The local surface topography must also have enough relief to create a hydraulic head and move water through the subsurface. Deposits susceptible to piping must be fine grained and uncemented, but permeable enough to allow subsurface movement of water. Finally, a free face or cliff is necessary for water and sediment to exit the deposit (Costa and Baker, 1981).

Deposits susceptible to piping are found throughout Utah, but most occur in the southeastern part of the state. Types of material susceptible to piping include fine-grained alluvium, fine-grained rock (siltstone, mudstone, and claystone), and volcanic tuff and ash. Holocene-age (10,000 years ago to present) alluvial fill in canyon bottoms in the Colorado Plateau is the most common material susceptible to piping in Utah (appendix 2). Claystone in this area is the next most likely material to develop pipes. Outside the Colorado Plateau, fine-grained marl and silt deposited by Lake Bonneville are susceptible to piping in the western and northern deserts of Utah (C.G. Oviatt, Kansas State University, oral communication, November, 1989).

Piping can cause damage to any structure built on soil subject to piping. Earthfill structures such as dams may also be susceptible to piping, and piping of fine-grained embankment materials at the base of the Quail Creek dike, near St. George, contributed to its failure in 1989 (James and others, 1989). In the Uinta Basin, irrigation of cropland adjacent to incised drainages has caused extensive piping. In areas where piping is common, roads are most frequently damaged because they commonly parallel stream drainages and cross-cut numerous pipes. In addition their construction commonly disturbs natural runoff, concentrating it near the roads.

Because of their association with canyon-bottom stream drainages, soils subject to piping are difficult to portray at the scale of this map. Therefore, areas affected by piping are not shown. Most drainages in southeastern and parts of western and southwestern Utah contain deposits susceptible to piping. Roads in these areas should be carefully located and properly drained.

Damage caused by piping can be reduced by limiting the degree to which natural drainage in soil susceptible to piping is disturbed by construction. Runoff concentrated or ponded along paved surfaces allows greater infiltration and crates a potential for pipes to develop. Proper drainage along roads and around structures is the most cost effective and successful mitigation procedure. Culverts to collect runoff, and closed conduits to carry the water away from the road, will prevent damage. Concrete-lined drainage ditches and concrete or asphalt around culvert inlets and outlets can also limit damage. Damage to cropland can likewise be reduced by reducing the amount of irrigation along incised stream drainages.

Sand Dunes

Dunes are common surficial deposits in arid areas where sand derived from the weathering of rock or from unconsolidated deposits is blown by the wind into mounds or ridges (figure 11). Dune fields are also common and are composed of many dunes of similar composition, oriented in a similar direction, and isolated from other dunes (Dean, 1978). Dunes in Utah are composed of three types of materials. The most common is silica (quartz), which makes up approximately 60 percent of all dunes. Thirty percent of Utah's dunes are composed of gypsum, and oolitic (calcium carbonate) dunes make up the remaining 10 percent. Dunes occur downwind of source areas, which include rock outcrops and alluvial and lacustrine sands for silica dunes, playas for gypsum dunes, and the shore of Great Salt Lake for oolitic dunes. Dunes are widespread throughout western Utah where vegetation is sparse and prevailing winds can readily move sandy sediments.

Intermontane basin fill consisting of alluvial and lacustrine fine sand, silt, and clay eroded and transported from rock in surrounding mountains is the main source for silica dunes. These dunes are commonly found on the west side of mountain ranges in western Utah where winds deposit the sand. Gypsum in dunes is derived from the evaporation and eventual crystallization of gypsum minerals during the seasonal wetting and drying of playa surfaces. When these lakes dry out, the sand-size crystals are moved by the wind and accumulate as dunes (figure 12). Oolitic dunes are composed of calcium carbonate, generally precipitated around a nucleus of fecal pellets from brine shrimp. They form in shallow water near the wave wash zone in Great Salt Lake, and previously formed along Lake Bonneville shorelines. During low lake levels, winds rework oolitic beach deposits into dunes. Many of the oolitic dunes in the Great Salt Lake Desert are reworked early Holocene beach deposits associated with prehistoric high levels of the Great Salt Lake.

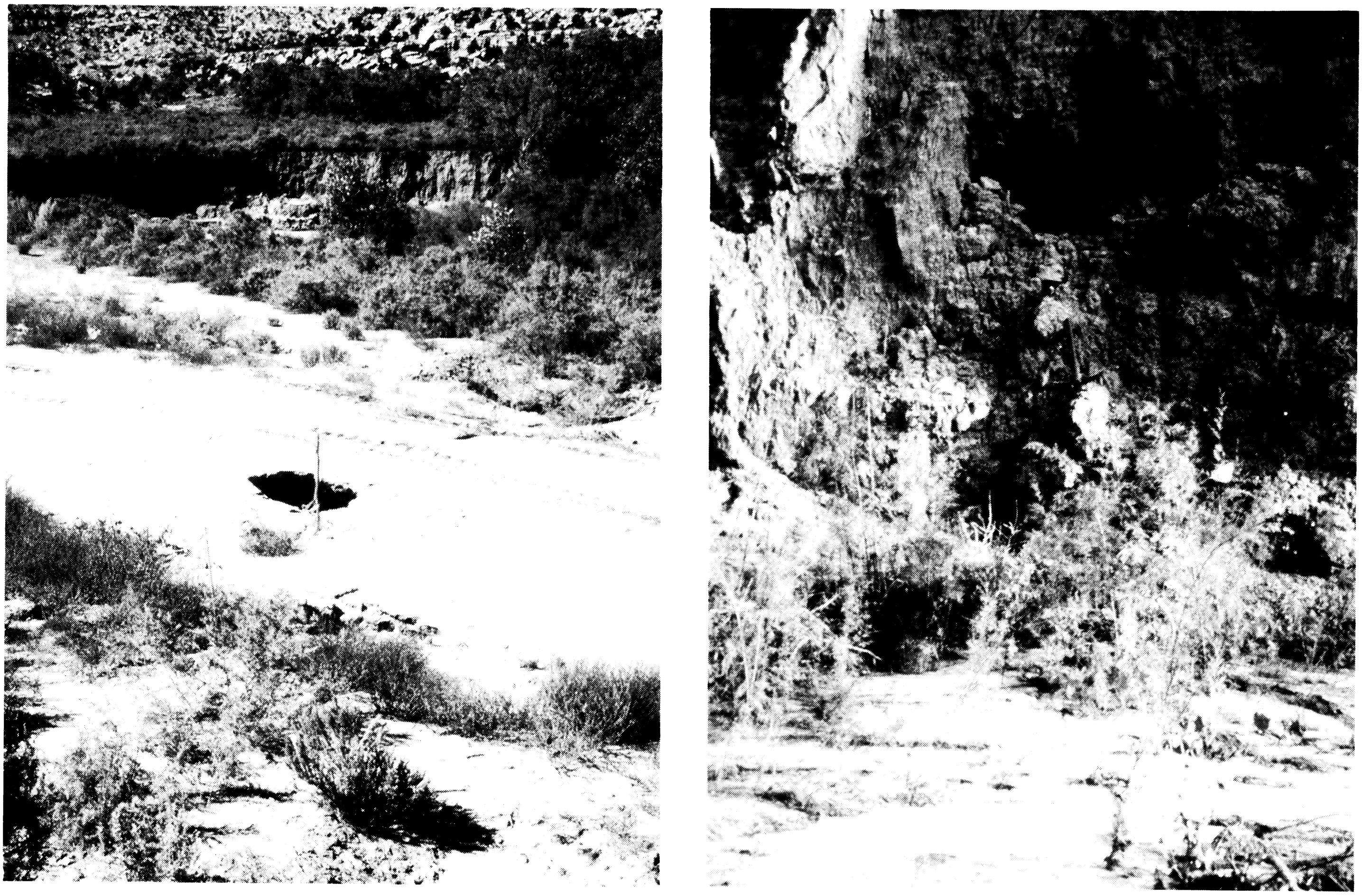


Figure 10. A, Pipe in road surface over Holocene alluvium along the drainage of Montezuma Creek in San Juan County, Utah, and B, pipe exiting stream bank (photos G.E. Christenson).

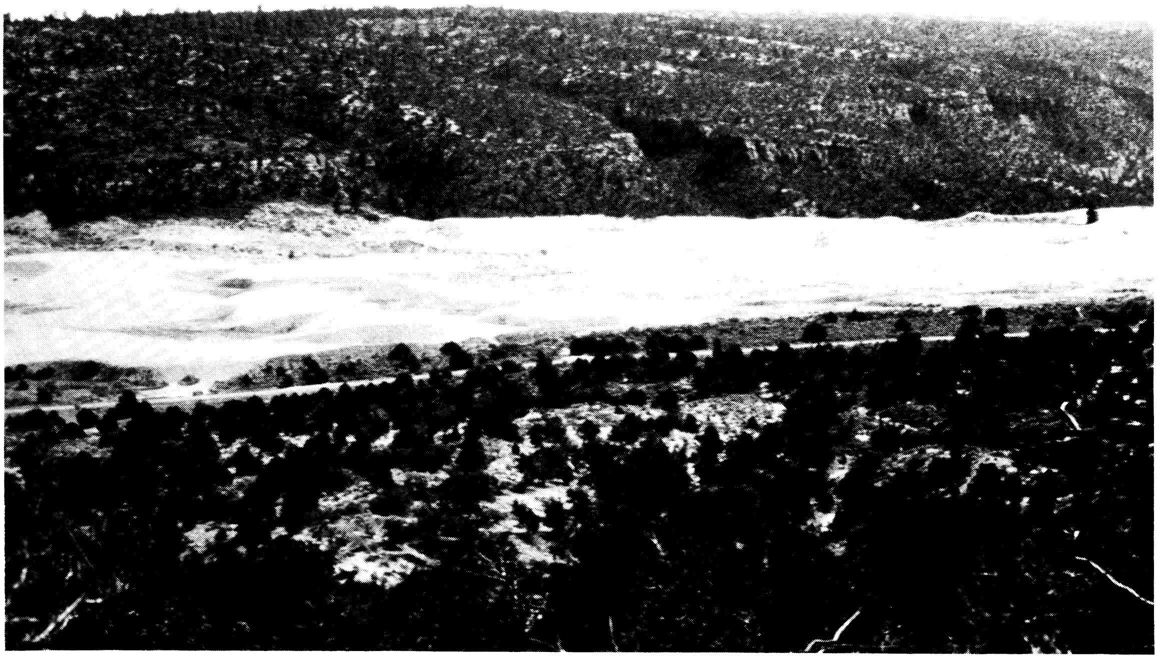


Figure 11. Coral Pink sand dunes (silica) in Kane County, Utah (photo G.E. Christenson).

Silica dunes are most common in western Utah, from the southern end of Tooele and Skull Valleys to the Escalante Desert north of Enterprise. Gypsum dunes are found in the greatest concentration in the Great Salt Lake Desert south and east of the Bonneville Salt Flats. They are also found along the lee side of many playas in the basins west of Delta. Oolitic dunes are very localized and are concentrated in the north-central portion of the state. They are found only in association with oolitic sand beaches along Great Salt Lake and in the Great Salt Lake Desert, where oolitic sands form early Holocene beach ridges (Solomon and Black, 1990).

In areas where development encroaches on dunes, several problems may occur. The most common problem associated with dunes is the destabilization of inactive or vegetated dunes by construction. The disturbed dunes may become reactivated, migrate over roads, and bury structures. Burial of structures by migrating dunes is also a problem where structures have been built near active dunes (figure 13). Contamination of ground water from wastewater disposal systems constructed in dune sand may also be a problem. Dunes consist of uniform-size sand grains and lack the fine clay and silt which help to filter effluent before it reaches the water table. Because of the uniform grain size, dune sand is highly permeable and allows effluent to move rapidly into the ground-water system. However, too much fine material can also be a problem. Drain field lines in dunes in Ivins became clogged by fine sand causing them to fail. All of these factors combine to make dune sands an unsuitable medium for wastewater disposal. Gypsiferous dunes would be an especially poor wastewater disposal medium as the gypsum would dissolve when wetted.

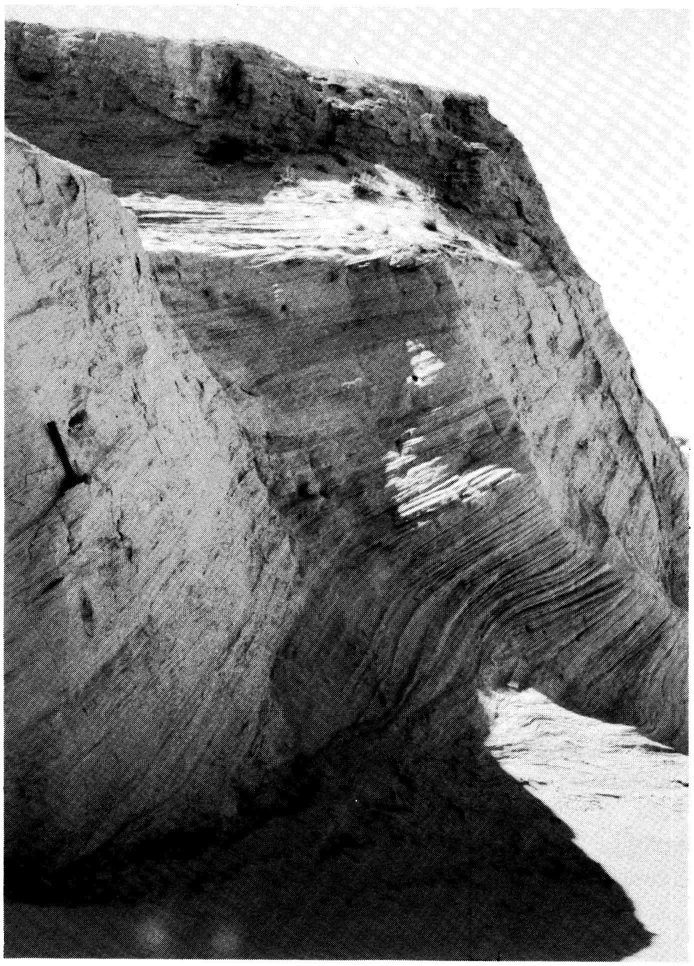


Figure 12. Gypsum dunes in the Great Salt Lake Desert (photo B. J. Solomon.

Effective mitigation practices for sand dune areas involve avoiding building on, or disposing of wastewater in, such deposits. Any disturbance can reactivate dunes stabilized by vegetative cover. Active dunes should be avoided because of their constant movement and unstable nature. In general, dunes are a maintenance problem and only in extreme cases do they preclude development.

Many small dune fields not shown on the map exist throughout Utah, especially in the eastern and southeastern portions of the state. They pose the same geologic hazards as the larger mapped dune fields, and the same care should be taken when beginning construction or disturbing dunes in any way.

Peat

Peat is an unconsolidated surficial deposit of partially decomposed plant remains. It usually accumulates in areas of shallow ground water and near standing water. These environments are anaerobic, or depleted in oxygen, which limits the rate of decay. Topography and climate influence decay rates, and low-lying areas and moist climates provide conditions conducive to accumulation of peat. Plant parts are still visible in most peat deposits but make up only 10 percent of the deposit; the remaining 90 percent is moisture (Costa and Baker, 1981). These organic-rich deposits have a high water-holding capacity and consequently shrink and oxidize rapidly when drained (Costa and Baker, 1981).

Due to the generally dry climate of Utah, peat deposits are very localized. They are found in poorly drained areas along the shores of Great Salt Lake, Utah Lake, and in low areas formerly occupied by Lake Bonneville. In mountainous areas, peat commonly forms in poorly drained depressions behind glacial moraines or in the head areas of large landslides.

Several geologic hazards can affect structures built on peat deposits. When water is removed from the deposit, it oxidizes rapidly and subsides. Peat also is highly compressible and has a low bearing strength, and it is subject to extreme settlement when loaded. In the longer term, decomposition of organic material may cause further subsidence. Dry peat deposits can also be fire hazards, as they will smoulder and burn if ignited. In general, peat deposits should be removed, avoided, or preconsolidated when encountered at construction sites.

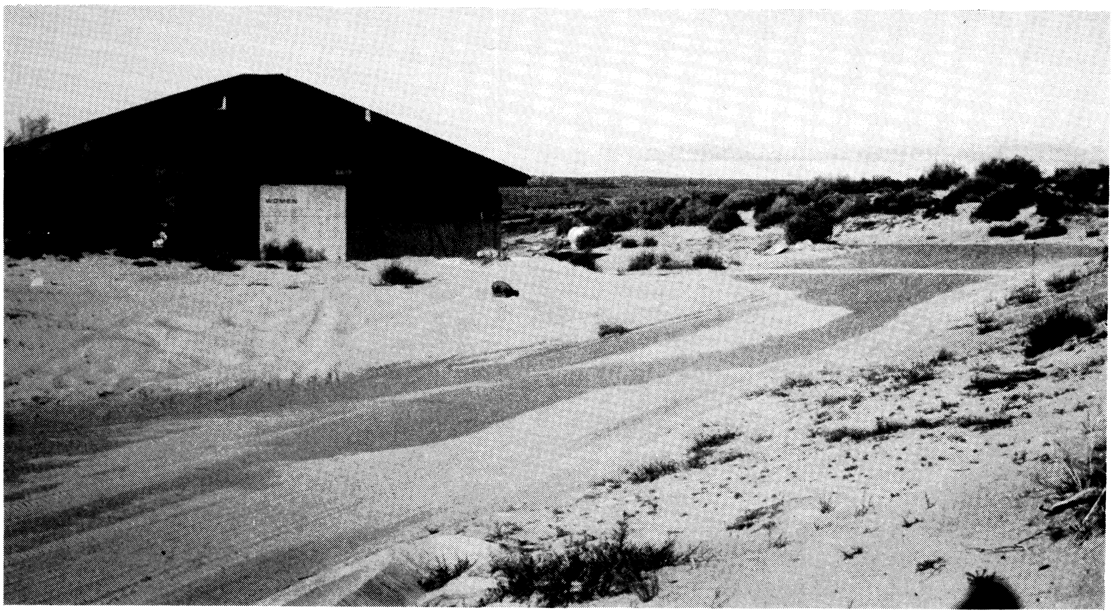


Figure 13. Oolitic dunes covering roads at Antelope Island State Park (photo Suzanne Hecker).

OTHER PROBLEMS

Mine Subsidence

Mine subsidence occurs above both active and abandoned mines in Utah. The removal of rock from the subsurface can cause subsidence of the land surface above as the void left by mining is filled by collapse of overlying material. The long history of mining in Utah has created many areas with surface subsidence or sinkholes (figure 14). Companies removing rock from the subsurface are now required by law to devise a mining method that reduces the potential for surface subsidence and to monitor subsidence and file a report with the Utah Division of Oil, Gas and Mining (DOGM) each year. The subsidence investigations are based on surveyed grids laid out over mining areas. If subsidence occurs, the mine is required to alter their mining methods to prevent further subsidence (A.C. Keith, Utah Geological Survey, oral communication, January, 1990). Data documenting subsidence in mines throughout Utah are not readily available and therefore mine-induced subsidence is not shown on this map. However, the limited information which is available indicates that, in general, most mines experience some subsidence each year. Most of the large active coal mines are concentrated in the Book Cliffs and Wasatch Plateau areas. Other areas where documented mine subsidence has occurred are the Park City mining district and the Tintic mining district around Eureka, Utah. In both of these areas, sinkholes have formed due to collapse of underground workings, but only in Eureka were structures damaged. The DOGM has approximately 1,100 mines listed in their abandoned mines data file. Listings of the location of these mines and their condition can be obtained from DOGM.

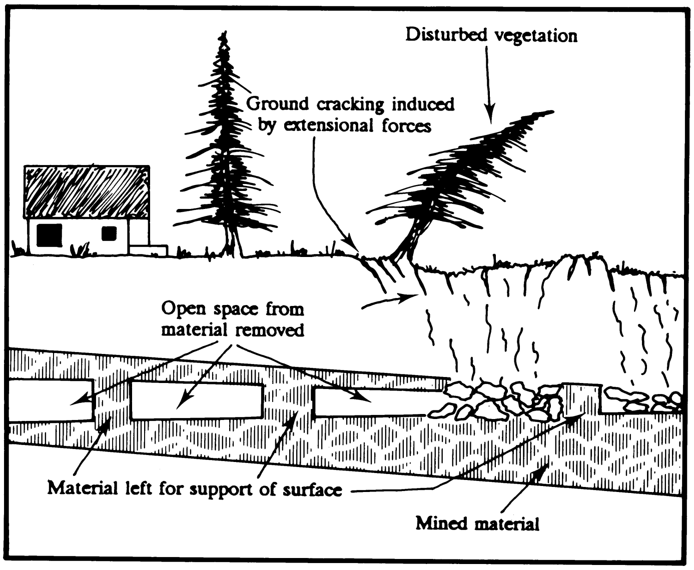


Figure 14. Schematic cross section of surface subsidence caused by collapse of underground mine workings.

Sodium Sulfate

The presence of sodium sulfate in soil throughout the western Great Basin has recently come to the attention of geologists with the U.S. Soil Conservation Service because of damage to earthen dams and irrigation structures (figure 15). Soil with a high concentration of water-soluble sulfates (thenardite, mirabolite) exhibits an expansive phenomenon resembling that of expansive clays and frost heave (Blaser and Scherer,

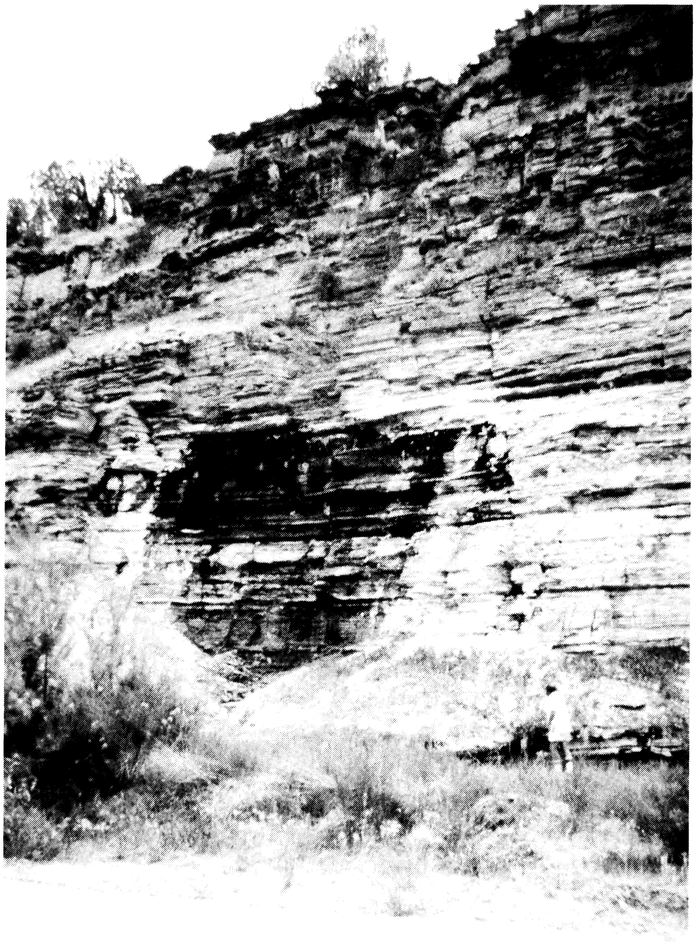


Figure 15. Sodium sulfate-rich ground-water seeps in the Green River Formation, near Duchesne, Utah (photo W.E. Mulvey).

1969). Sodium sulfate is deposited upon evaporation of surface waters in playas. It has been identified, however, in many areas other than playas and appears to be introduced as an airborne particulate. In some cases the sodium sulfate is derived from a bedrock source such as in Duchesne County, where the saline facies of the Green River Formation introduces sodium sulfate into the local surface and ground water (R.C. Rasely, U.S. Soil Conservation Service, oral communication, November, 1989).

Several areas in Utah have higher than average concentrations of sodium sulfate in the soil. Laboratory tests by the U.S. Soil Conservation Service determined that sodium sulfate-rich soil was present in the highlands north of St. George, Utah, and in fill used for dams impounding stock ponds in the Blue Creek-Howell watershed in Box Elder County, Utah. Most sodium sulfate in northern Utah has its source in the fine-grained, deep-water sediments left by Lake Bonneville.

Problems associated with sodium sulfate in soil include deterioration of cement in concrete, and expansion and contraction similar to that experienced in expansive soil and rock. When sodium sulfate comes in contact with concrete a chemical reaction takes place causing the cement in the concrete to deteriorate. This can be avoided by the use of commercially available sodium-sulfate resistant concrete. Expansive characteristics of sodium sulfate soil in Utah are not well known. Mitigation procedures are similar to those listed above for expansive soil. Soil chemistry tests to determine the presence of sodium sulfate prior to construction are recommended.

CONCLUSIONS AND RECOMMENDATIONS

Problem soil and rock are some of the most widespread geologic hazards in Utah. They cover approximately 20 percent of the state and underlie many urbanized areas. Some types of problem soil and rock occur over large areas, whereas others are found only locally. It is likely that more areas are affected by problem soils and rock than are shown on the map, but because of the limited information available only recognized areas are shown.

The two most widespread problem deposits are expansive soil and rock derived from marine shale, and limestone and dolomite susceptible to dissolution. Expansive soil and rock occurs over much of the Uinta Basin and south-central Utah. Limestone and dolomite are found in central and western Utah, but the greatest concentration is in the north-central part of the state. Along the mountain fronts from Provo south to the Arizona border, collapsible soil may be found in alluvial-fan sediments. Dunes are scattered throughout the western deserts, and soils subject to piping are found primarily in drainages incised into Holocene alluvium in canyons of eastern Utah. Peat deposits are found around the shores of Great Salt Lake and Utah Lake, as well as in mountain drainages dammed by glacial moraines and landslides. Subsidence due to collapse of underground workings has occurred in Park City and Eureka, above mines in the Book Cliffs, and on the eastern slope of the Wasatch Plateau. Sodium sulfate-rich soil is known to occur throughout western Utah and parts of the Uinta Basin.

Most of the hazards created by these problem soil and rock can be mitigated or avoided if they are understood and their areal extent is known. This map and text are a first step in identifying areas where problem soil and rock are known to occur and have caused damage. It also delineates areas where problems may be expected. The information on the map should be used by local governments and the private sector to identify where problem deposits may occur and where site-specific studies are advisable prior to development. However, because of the small scale of the map it should not be used as a substitute for a detailed site-specific investigation. Recognizing that problem soil and rock cover parts of the state and taking precautions to mitigate the potential hazards they represent can reduce the need for costly corrective measures after damage to structures and roads has occurred.

ACKNOWLEDGMENTS

Gary E. Christenson at UGS was helpful in setting up the project and providing guidance. Fitz Davis and Alec Keith of the UGS provided helpful discussions concerning soil problems and mine subsidence, respectively. Kimm Harty, Gary Christenson, and Bill Lund of UGMS, Pat Rogers of the Colorado Geological Survey and R.C. Rasely of the U.S. Soil Conservation Service reviewed the text. R.C. Rasely provided access to his library and personal experience with problems concerning sodium sulfate-rich soils. C.G. Oviatt provided much needed information on deposits in the western basins of Utah. Kimm Harty, Suzanne Hecker, and Janine Jarva produced the UGS Hazards Bibliography from which most of the data for this compilation were identified.

REFERENCES IN TEXT

Bauman, R.D., 1964, Heave stabilization of Mancos Shale: Unpublished masters thesis, University of Utah Department of Civil Engineering, 72 p.

Bell, F.G., 1983, Engineering properties of soils and rocks: London, Butterworths, 149 p.

Blaser, H.D., and Scherer, O.J., 1969, Expansion of soils containing sodium sulfate caused by drop in ambient temperatures: Federal Highway Research Board Special Report 103, p. 150-160.

Cooke, R.U., and Warren, Andrew, 1973, Geomorphology in deserts: Berkeley, University of California Press, 394 p.

Costa, J.E., and Baker, V.R., 1981, Surficial geology building with the earth: New York, John R. Wiley and Sons, 498 p.

Dean, L.E., 1978, Eolian sand dunes of the Great Salt Lake Basin: Utah Geological and Mineral Survey, Utah Geology v. 5, no. 2, p. 103-111.

James, R.L., Catanach, R.B., O'Neill, A.L., and Von Thun, J.L., 1989, Investigation of the cause of Quail Creek Dike failure: Report of Independent Review Team to the Honorable Norman H. Bangerter, Governor of Utah, 155 p.

Jammal, S.E., 1984, Maturation of the Winter Park sinkhole, *in* Beck, B.F., editor, Sinkholes: their geology, engineering & environmental impact: Proceedings of the First Multidisciplinary Conference on Sinkholes, Orlando Florida,October, 1984, p. 363-369.

Jennings, J.N., 1985, Karst geomorphology: Oxford, Basil Blackwell, 293 p.

Kaliser, B.N., 1978, Ground surface subsidence in Cedar City, Utah: Utah Geological and Mineral Survey Report of Investigation 124, 130 p.

Solomon, B.J., and Black, B.D., 1990, Quaternary geology and geological hazards of the West Desert Hazardous Industry Area, Tooele County, Utah, *in* Robinson, Lee, editor, Proceedings of the Annual Symposium on Engineering Geology & Geotechnical Engineering, p. 5-1-14, Pocatello, Idaho, Idaho State University.

Tourtelot, H.A., 1974, Geologic origin and distribution of swelling clays: Bulletin of the Association of Engineering Geologists, v. XI, no. 4, p. 259-275.

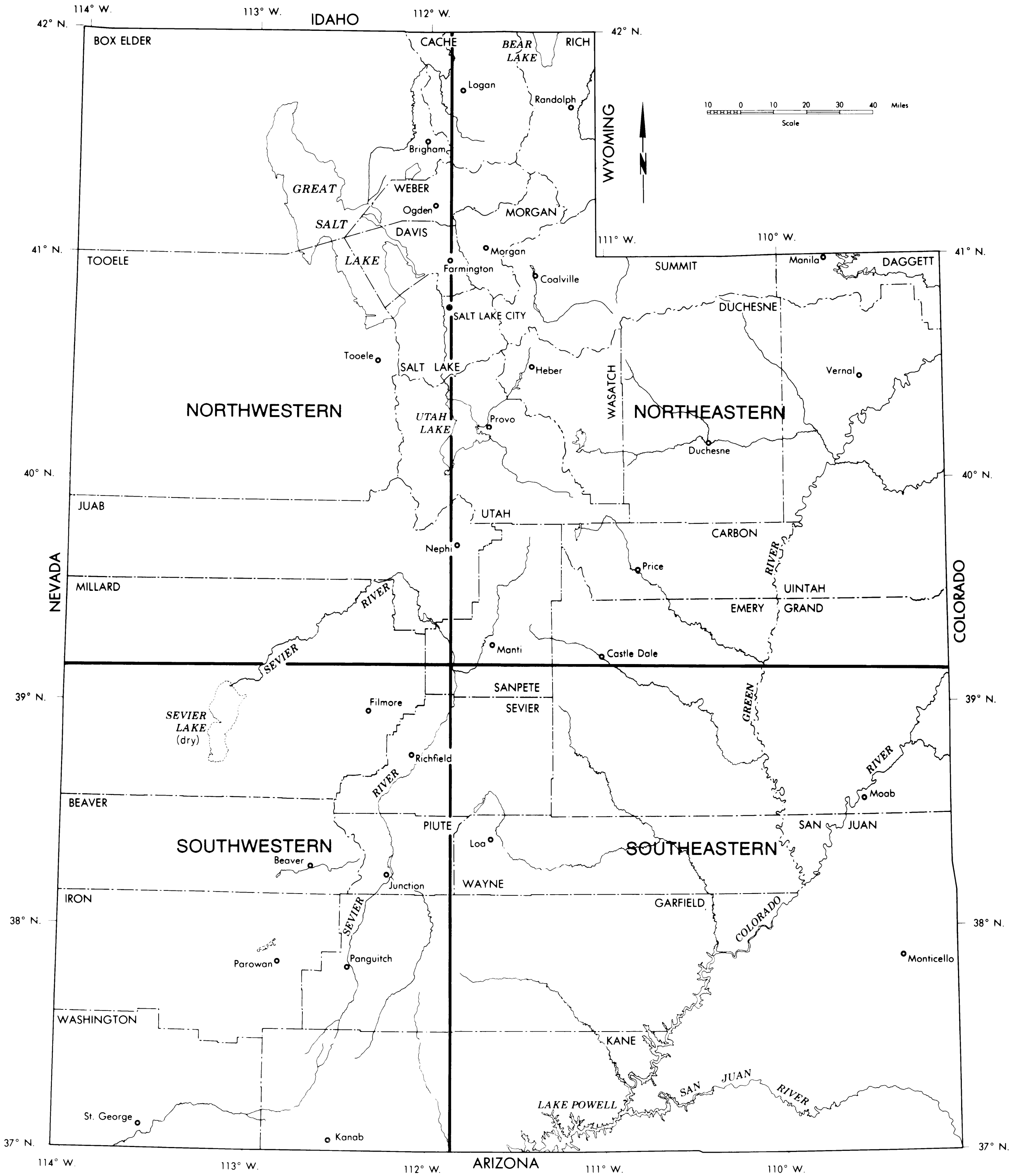
APPENDIX

Appendix 1

Subdivisions of Geologic Time			Apparent Ages (millions of years before present)
Eras	Periods	Epochs	
CENOZOIC	Quaternary	(Recent) Holocene	**.01**
		Pleistocene	**1.6**
	Tertiary	Pliocene	**5**
		Miocene	**24**
		Oligocene	**38**
		Eocene	**55**
		Paleocene	**66**
MESOZOIC	Cretaceous		**138**
	Jurassic		**205**
	Triassic		**240**
PALEOZOIC	Permian		**290**
	Pennsylvanian (Upper Carboniferous)		**330**
	Mississippian (Lower Carboniferous)		**360**
	Devonian		**410**
	Silurian		**435**
	Ordovician		**500**
	Cambrian		**570**
PRECAMBRIAN			

General geologic time scale.

Appendix 2



Quadrant designations for engineering-geologic problems in Utah (see following table).

Appendix 2. Geologic units causing engineering geologic problems in Utah.

PROBLEM	NORTHWEST	NORTHEAST	SOUTHEAST	SOUTHWEST
Expansive soils & rocks	Norwood Tuff, Manning Canyon Shale, Morrison Formation, Arapien Shale and Ankareh Shale.	Mancos Shale, Hilliard Shale, Blair Formation, Morrison Formation, Chinle Shale, Moenkopi Formation, Ankareh Shale, Arapien Shale, Norwood Tuff.	Morrison Formation, Chinle Shale, and Moenkopi Formation.	Tropic Shale, Arapien Shale, Chinle Formation, and Moenkopi Formation.
Hydrocompaction (collapsible soils)	Throughout Utah; Holocene-age debris-flow and alluvial-fan sediments along mountain front or similar depositional environment.	Same as Northwest.	Same as Northwest.	Same as Northwest.
Gypsiferous soils and rocks		Dry Gulch Member of Green River Formation.		Moenkopi Formation (Shnabkaib Member), Arapien Shale, Carmel Formation; near St. George gypsum layers form just above the water table.
Limestone	Round Valley Limestone, Great Blue and Humbug Limestone, Lodgepole Limestone, Laketown Dolomite, Fish Haven Dolomite, Garden City Limestone, Ochre Mountain Limestone, Joana Limestone, Notch Peak Formation, Guilmette Formation.	Round VaUey Limestone, Great Blue and Humbug Limestone, Lodgepole Limestone, Laketown Dolomite, Fish Haven Dolomite, Garden City Limestone, Twin Creek Limestone, Deseret Limestone, Gardison Limestone, Kirkman Limestone, Opohonga Limestone, Maxfield and Madison Limestones.	Kaibab Limestone.	Ochre Mountain Limestone, Joana Limestone, Laketown Dolomite, Notch Peak Formation, Flagstaff Limestone, Kaibab Limestone.
Piping	Holocene alluvium along incised stream channels.	Same as Northwest.	Same as Northwest.	Same as Northwest.
Dunes	Dunes are widely distributed in western Utah; three types are common: silica, gypsum, and oolitic. Most numerous are ones composed of silica sands.		Many smaller dune fields are present throughout this region but, due to their size, are not included on the map.	Silicic dunes are found in the Escalante Desert area.
Peat	Potential for peat deposits around the shorelines of Great Salt Lake, Utah Lake, and floodplains.	Low areas along the Bear River, alpine meadows in the Bear River Range and other ranges.		

Appendix 3

LIST OF REFERENCES USED TO COMPILE THE MAP

Airphoto Analysis Associates, 1979, Integrated resources survey Wood Buffalo National Park, Alberta, N.W.T.: Ontario, variously paginated.

Bauman, R.D., 1964, Heave stabilization of Mancos Shale: Unpublished masters thesis, University of Utah, 80 p.

Beason, S.C., 1979, Evaluation of geologic implications regarding Tyzack aqueduct and pumping plant, Jensen Unit, Central Utah Project, Utah: U.S. Bureau of Reclamation unpublished report G-305A, unpaginated.

- - - 1986, Final construction geology report for Vat Tunnel, Strawberry Aqueduct, Bonneville Unit, Central Utah Project, Utah: U. S. Bureau of Reclamation unpublished report 6-358, 89 p.

Beck, B.F., 1984, Sinkholes: their geology, engineering & environmental impact: Proceedings of the First Multidisciplinary Conference on Sinkholes, Orlando, Florida,429 p.

Birkeland, P.W., 1984, Soils and geomorphology: New York, Oxford University Press, 372 p.

Bjorklund, L. J., and Robinson, G. B., Jr., 1968, Ground water resources of the Sevier River Basin between Yuba Dam and Leamington Canyon, Utah: U. S. Geological Survey Water-Supply Paper 1848, 79 p.

Bridges, B. L., 1957, Basin Creek Reservoir site, West Box Elder Soil Conservation District Area 1: U. S. Soil Conservation Survey unpublished memorandum, 2 p.

- - -, 1977a, Brief geologic report on dam construction in Utah: U.S. Soil Conservation Service unpublished report, variously paginated.

- - - 1977b, Geologic hazard report dam nos. 2(12a), 3(12b), 4(12c), 5(12d), Greens Lake Watershed, Iron County, Utah: U.S. Soil Conservation Service unpublished report, 3 p.

Brooks, S. J., 1989, A comparison of salt thickness on the Bonneville Salt Flats, Tooele County, Utah, during July, 1960, October 1974, and October 1988, and summary of prior investigations: U. S. Bureau of Reclamation unpublished technical memo, 38 p.

Bull, W.B., 1964, Alluvial fans and near-surface subsidence in western Fresno County, California: U.S. Geological Survey Professional Paper 437-A, 70 p.

Chen and Associates, Inc., 1980a, Preliminary geologic and soils investigation for properties in sections 20, 21, & 28, Silver Creek Junction, Summit County, Utah: Unpublished consultant's report 140U, 14 p.

- - - 1980b, Preliminary geology and soils investigation for the initial phase Silver Creek Community, Summit County, Utah: Unpublished consultant's report No. 143U, 13 p.

- - - 1983a, Geotechnical investigation of microwave tower, Roosevelt, Utah: Unpublished consultant's report 465U, 9 p.

- - - 1983b, Geotechnical investigation, church building, Cleveland, Utah: Unpublished consultant's report 294U, 11 p.

- - - 1983c, Geotechnical investigation, proposed 7-Eleven store, northeast corner of 200 West Street and Main Street, Hurricane, Utah: Unpublished consultant's report, 512-U, 6 p.

- - - 1984, Preliminary geologic investigation, United States Pollution Control Inc, hazardous and non-hazardous waste disposal landfills, Grassy Mountain facility, Knolls, Utah: Unpublished consultant's report 527584, 16 p.

- - - 1988, Geotechnical investigation Davis County Criminal Justice Complex, Clark Lane and 650 West, Farmington, Utah: Unpublished consultant's report Job No. 511088, 17 p.

Christenson, G.E.,1981a, Engineering geology for land-use planning, Ballard, Utah: Utah Geological and Mineral Survey Report of Investigation 167, 13 p.

- - - 1981b, Inspection of Captain's Cove Subdivision, Manila, Daggett County: Utah Geological and Mineral Survey unpublished memorandum, 4 p.

- - - 1982, Ground cracking and subsidence in the Nephi area, Juab County, Utah: Utah Geological and Mineral Survey unpublished memorandum, 5 p.

- - - 1984, Sinkhole in Cedar View Subdivision near Vernal, Utah: Utah Geological and Mineral Survey unpublished memorandom 3p.

- - - 1983 Field trip guide to the engineering geology of southwest Utah: Association of Engineering Geologists, Utah Section, 18 p.

- - - 1985, Investigation of seven school sites in Washington County, Utah, *in* Harty, K.M., compiler., Technical Reports for 1984 Site Investigation Section: Utah Geological and Mineral Survey Report of Investigation 198, p. 51-62.

- - - 1986, Utah's geologic hazards: Utah Geological and Mineral Survey, Survey Notes, v. 20, no. 1, p. 3-8.

Christenson, G.E. and Dean, R.D., 1983, Engineering geology of St. George area, Washington County, Utah: Utah Geological and Mineral Survey Special Studies 58, 32 p.

Costa, J.E., and Baker, V.R., 1981, Surficial geology building with the earth: New York, John R. Wiley & Sons, 498 p.

Coon, King and Knowlton, 1977, Settlement of home in Cedar City , Utah: Unpublished consultant's report, 3 p.

Curtin, George, 1973, Collapsing soil and subsidence, *in* Moran, D.E., Slosson, J.E., Stone, R.O., and Yelverton,C.A., editors., Geology, seismicity, and environmental impact: Association of Engineering Geologists Special Publication, October, 1973, p. 89-100.

Dames and Moore, 1960, Report of foundation investigation, proposed womens dormitories, College of Southern Utah, Cedar City, Utah: Unpublished consultant's report for the Utah State Building Board, Job no. 04000-001-06, 4 p.

- - - 1961, Report of foundation investigation, proposed Iron County Hospital, Cedar City, Utah for Iron County: Unpublished consultant's report, Job no. 04016-001-06, 4 p.

- - - 1966, Report of investigation studies - adverse movement, Visitors Center Building, Dinosaur National Monument: Unpublished report for the National Park Service, Job No. 02050-014-06, 12 p.

- - - 1970a, Report of foundation investigation proposed administration building, Southern Utah State College, Cedar City, Utah, for the

Utah State Building Board: Unpublished consultant's report, Job 04000-016-06, 70 p.

--- 1970b, Report of foundation investigation,proposed married student apartments, Southern Utah State College, Cedar City, Utah for Utah State Building Board: Unpublished consultant's report, Job no. 04000-015-06, 10 p.

--- 1972, Report of foundation investigation proposed bank building, Cedar City, Utah: Unpublished consultant's report, Job 02053-011-06, 8 p.

--- 1973a, Report of foundation investigation proposed Sheraton Motor Inn - Convention Center, Park City, Utah: Unpublished consultants report Job No. 06443-00106, 10 p.

--- 1973b, Report of foundation investigation proposed tailings disposal system near Tooele, Utah:Unpublished consultant's report, Job No. 06443-001-06, 10 p.

--- 1978, Phase I, preliminary geologic studies, proposed power plant lower Sevier River area, Utah: Unpublished consultant's report for IntermountainPower Project, Job no. 10629-002-06, 26 p.

--- 1985, Preliminary soils and foundation investigation - alternate sites 1 & 10 proposed high school, Vernal, Utah: Unpublished consultant'sreport, Job No. 13326-001-06, 17 p.

--- 1986, Summary report subsidence investigation residential area near 1500 East and Millbrook Way, Bountiful, Utah: Unpublished consultant's report, Job No. 09814-005-06, 10 p.

Dames and Moore, Ralph M. Parsons Company, and Roger Foott Associates, Inc., 1987, Site proposal for the Superconducting Super Collider, Cedar Mountain site, Volume 3 - geology and tunneling: Proposal appendix A - Volumes 1,2,3.

Davis, F.D., 1989, Water-related geologic problems of 1983 in southeastern Utah: Utah Geological and Mineral Survey Open-File Report 149, 89 p.

Dean, L.E., 1978, Eolian sand dunes of the Great Salt Lake Basin: Utah Geological and Mineral Survey, Utah Geology, v. 5, no. 2, p. 103 - 111.

DeGraff, J.V., 1978, Geologic investigation of sinkholes adjacent to the Skumpah Reservation Dams: U.S. Forest Service unpublished memorandum, 3 p.

--- 1979, Subsidence tension cracks: Initial assessment of "self-healing" rates and magnitude: Geological Society of America Abstracts with Programs, v. 11, no. 7, p. 411.

--- 1980, Geologic survey of two accelerated erosion areas near Taylor Flat in Salina Canyon: U.S. Forest Service unpublished memorandum, 3 p.

Delta Geotechnical Consultants, Inc., 1983a, Geotechnical studies proposed Tooele County Recreation Center, 730 West 200 North, Tooele, Utah: Unpublished consultant's report, 1286, 7 p.

--- 1983b, Investigation of building movement, the Ridges Condominium, Wellington, Utah: Unpublished consultant's report, 1243, 8 p.

--- 1983c, Geotechnical enginering services, Oquirrh Service Center, 5783 West 4100 South, West Valley City, Utah: Unpublished consultants report, 1303, 8 p.

--- 1985a, Building distress study 1686 East 800 North Price, Utah: Unpublished consultants report 1719, 10 p.

--- 1985b, Building distress study 1450 East, Cottonwood Village, # 3, Price, Utah: Unpublished consultants report 1621, 12 p.

--- 1985c, Building distress study, 700 Molyneaux Drive, Price, Utah: Unpublished consultants report 1691, 6 p.

--- 1985d, Building distress study 1618 Hilltop Drive, Maeser, Utah: Unpublished consultant's report 1628, 9 p.

--- 1985e, Building distress study 4721 West Hillside Drive, Maeser, Utah: Unpublished consultant's report 1627, 11 p.

--- 1985f, Geotechnical study proposed Iron County Jail/Resource Center, 2136 West Main, Cedar City, Utah: Unpublished consultant's report 1545, 15 p.

--- 1985g, Building distress study at 764 Windsor Circle, Price, Utah: Unpublished consultants report 1586, 10 p.

--- 1986, Geotechnical study Roosevelt 3rd & 10th Wards and Roosevelt, Utah East Stake Center, 500 North and 600 East, Roosevelt, Utah: Unpublished consultant's report 1785, 13 p.

Demming, M.R., 1976, Preliminary geology report Dry Wash dam site, Kane County, Glendale, Utah: U.S. Soil Conservation Service unpublished report, 6 p.

Doelling, H.H., 1980, Geology and mineral resources of Box Elder County, Utah: Utah Geological and Mineral Survey Bulletin 115, 251 p.

Doelling, H. H., and Davis, F. D., 1989, Geology of Kane County, Utah: Utah Geological and Mineral Survey Bulletin 124, 192 p.

Dow, K.A., Owens, R.L., Stone, L.W., Strain, R.T., and Weins, C.L., 1988, Geologic design data report Diamond Fork pipeline and access road, Vol. 1,2,3: U.S. Bureau of Reclamation unpublished report G-437, 152 p.

Einert, Martin, and Sandberg, Sally,, 1986, La Verkin Springs Unit, Utah sinkhole activity in 1985: U.S. Bureau of Reclamation unpublished preliminary report, 7 p.

Everitt, B.L., 1982, Proposed well for Scipio Irrigation Company: Utah Division of Water Resources unpublished memorandum, 5 p.

--- 1985, Laketown Project: Utah Department of Water Resources unpublished memorandum, 2 p.

--- 1986, Summary and recommendations for study of groundwater hydrology in Timpoweap Canyon: Utah Department of Water Resources unpublished memorandum, 5 p.

Everitt, B.L., and Aubrey, Dan, 1985a, Summary of the geology, Lower Fremont project: Utah Department of Water Resources unpublished memorandum, 6 p.

--- 1985, Inspection of Trees dam site in South Creek: Utah Department of Water Resources unpublished memorandum, 3 p.

Flint, R.F., and Denny, C.S., 1958, Quaternary geology of Boulder Mountain, Aquarius Plateau, Utah: U.S. Geological Survey Bulletin 1061-D, p. 103-164.

Fugro National, Inc., 1981, MX siting investigation preliminary geotechnical investigation proposed operation base site, Milford Utah, Volume I-synthesis: Unpublished consultant's report for U. S. Air Force, 48 p.

Gill, H.E., 1985, Geologic investigation for the new Tabiona Public School Building: Utah Geological and Mineral Survey unpublished memorandum, 2 p.

--- 1987a, Wallsburg Estates Subdivision, *in* Mulvey, W.E., comp., Technical reports for 1986, Site Investigation Section: Utah Geological and Mineral Survey Report of Investigation 215, p. 100-107.

--- 1987b, Kanab Creek Ranchos expansion individual waste-water disposal system investigation, Kane County, Utah, *in* Mulvey, W.E., compiler Technical reports for 1986, Site Investigation Section: Utah Geological and Mineral Survey Report of Investigation 215, pp. 92-99.

--- 1988, Fremont Junction geologic hazard evaluation, Sevier County Utah, *in* Black, B.D., compiler, Technical reports for 1987, Site Investigation Section: Utah Geological and Mineral Survey Report of Investigation 216, p. 83-89.

Gill. H.E., and Lund, W.R., 1984, Engineering geology of Park City, Summit County, Utah: Utah Geological and Mineral Survey Special Studies 66, 42 p.

Godfrey, A.E., 1985, Karst hydrology of south slope of Uinta Mountains, Utah: Utah Geological Association Guidebook 12, p. 277-293.

Griswold, D.H., 1955a, Pine Creek Reservoir site geology, Fremont River Soil Conservation District: U.S. Soil Conservation Service unpublished memorandum, 1 p.

Griswold, D.H., 1955b, Spectical Lake Reservoir: U.S. Soil Conservation Service unpublished memorandum, 1 p.

Harty, K.M., 1988, Preliminary hazards inventory for the Bear River Range Planning Unit, Cache and Rich Counties, *in* Black, B.D., compiler, Technical reports for 1987, Site Investigation Section: Utah Geological and Mineral Survey Report of Investigation 216, p. 104-114

Harty, K.M., and Christenson, G.E., 1988, Flood hazard from lakes and failure of dams in Utah: Utah Geological and Mineral Survey Map 111, scale 1:750,000.

Hecker, Suzanne, Harty, K.M., and Christenson, G.E., 1988, Shallow ground water and related hazards in Utah: Utah Geological and Mineral Survey Map 110, scale 1:750,000.

Hintze, L.F., 1980, Geologic map of Utah: Utah Geological and Mineral Survey, scale 1:500,000.

Hood, J.W., and Frush, F.E., 1965, Water resources of the Snake Valley area, Utah and Nevada: Utah State Engineer Technical Publication 68, 143 p.

Kaliser, B. N., 1971a, Preliminary reconnaissance of Kanab Creek Rancho development, Kane County: Utah Geological and Mineral Survey Report of Investigation 49, 2 p.

--- 1971b, Geologic hazards in Morgan County, with applications to planning: Utah Geological and Mineral Survey Report of Investigation 57, 94 p.

--- 1972, Environmental geology of Bear Lake area, Rich County, Utah: Utah Geological and Mineral Survey Bulletin 96, 32 p.

--- 1975, Geologic reconnaissance of southern Utah Bicentennial Amphitheater, Springdale, Utah: Utah Geological and Mineral Survey Report of Investigation 103, 4 p.

--- 1978, Ground surface subsidence in Cedar City, Utah: Utah Geological and Mineral Survey Report oflnvestigation 124, 130 p.

Kirchen, H.W., 1940, Preliminary geologic report, Porcupine Dam site Cache County, Utah, secondary investigation: U.S. Bureau of Reclamation unpublished report, 5 p.

Klauk, R.H., 1986a, Engineering geology for land use planning for Research Park, University of Utah, Salt Lake City, Utah: Utah Geological and Mineral Survey Report of Investigation 204, 27 p.

--- 1986b, Geologic hazards evaluation for a site in the Pole Canyon area, Spanish Fork Canyon, Utah County, *in* Mulvey, W.E., compiler, Technical reports for 1985, Site Investigation Section: Utah Geological and Mineral Survey Report of Investigation 208, p. 268-271.

Klauk, R.H., and Harty, K.M., 1988, Sinkhole and landslide investigation in Summit County, Utah, *in* Black, B.D., compiler, Technical reports for 1987, Site Investigation Section: Utah Geological and Mineral Survey Report of Investigation 216, p. 99-103.

Kleinfelder and Associates, 1985, Soils test findings for City of Santa Clara: Unpublished consultant's memorandum, 15 p.

Lovelace, E. E., 1980, Scipio to Sevier River, subsurface investigation for sinkhole problems: Utah Department of Transportation unpublished memorandum, 6 p.

Lowe, Mike, 1987, Garner residence, 880 North 325 West Bountiful: Utah Geological and Mineral Survey excavation inspection file, 1 p.

--- 1989, Excavation inspection, Foxbridge Subdivision, Centerville, Utah: Utah Geological and Mineral Survey excavation inspection file, 1 p.

--- (in prep.), Surficial geology of Ogden Valley, Weber County, Utah: Utah Geological Survey Open-File Report, 69 p.

Lund, W. R., 1979a, Geotechnical reconnaissance of Kanab City's wastewater treatment lagoon site: Utah Geological and Mineral Survey Report of Investigation 146, 18 p.

--- 1979b, Geologic reconnaissance of the Sherwood Shores Subdivision near Delta, Millard County, Utah: Utah Geological and Mineral Survey unpublished memorandum, 4 p.

--- 1979c, Site investigation for the physical education building at the College of Eastern Utah: Utah Geological and Mineral Survey unpublished memorandum, 4 p.

--- 1983, Geological evaluation of septic tank and soil absorption system suitability, Dry Fork Canyon, Uinta County, Utah: Utah Geological and Mineral Survey Report of Investigation 176, 31 p.

--- 1986, Geologic evaluation of three subdivisions in Duchesne County for installation of septic tank soil absorption field wastewater disposal systems, *in* Mulvey, W.E., compiler, Technical reports for 1985, Site Investigation Section: Utah Geological and Mineral Survey Report of Investigation 208, p. 205-214.

Lund, W.R., and Case, W.F., 1986, Geologic evaluation of proposed regional wastewater treatment plant site, Washington County, Utah: Utah Geological and Mineral Survey Report of Investigation 206, 22 p.

Montgomery, S. B., 1974, Investigation of Johnson Creek Sinks, Gosute Indian Reservation: Utah Division of Water Resources unpublished memorandum, 2 p.

--- 1978, Hydrogeologic investigation for culinary well site, Mantua Hatchery: Utah Department of Water Resources unpublished memorandum, 2 p.

Montgomery, S.B., and Deming, M.R., 1972, Preliminary geologic report Mill Creek Dam site and Sheley Dam site: Utah Division of Water Resources and U.S. Soil Conservation Service unpublished memorandum, 13 p.

Oviatt, C.G., 1989, Quaternary geology of part of the Sevier Desert, Millard County, Utah: Utah Geological and Mineral Survey Special Study 70, 41 p.

Oviatt, C.G., 1991, Quaternary geology of Fish Springs Flat, Juab County: Utah Geological Survey Special Study 77, 16 p., 1:50,000

Owens, R.L., and Rollins, K.M., 1990, Collapsible soil hazard map for the southern Wasatch Front: Utah Geological Survey Miscellaneous Publication 90-1, 38 p.

Palmer-Wilding Consulting Engineers, 1983, Smith and Moorehouse project geology report: Unpublished consultants report for the Utah State Division of Water Resources, 34 p.

- - - 1984, Site investigation with geology and engineering evaluation of the Hatchtown Dam and Reservoir, Garfield County, Utah: Unpublished consultant's report for Utah Department of Water Resources, 55 p.

Pampeyan, E.H., 1984, Geologic map of the Lynndyl 30'x 60' quadrangle Tooele, Juab, Utah, and Milford Counties, Utah: U.S. Geological Survey Open-File Report 84-660, scale 1:100,000.

Price, Don, and Bolke, E.L., 1970, Hydrologic reconnaissance of the Sink Valley area, Tooele and Box Elder Counties, Utah: Utah Department of Natural Resources Technical Publication 26, 34 p.

Prizio, J.V., 1984, Examination report of Lost Creek Dam for SEED program Weber Basin Project, Utah, Upper Colorado Region: U.S. Bureau of Reclamation unpublished memorandum, 29 p.

Rasely, R.C., 1982, Backhoe geologic investigation of Frog Hollow debris-basin sediment pool: U.S. Soil Conservation Service unpublished report, 3 p.

- - - 1984, Geologic report grade stabilization site No. GS-1, Blue Creek-Howell Watershed, Box Elder County, Utah: U.S. Soil Conservation Service unpublished report, 10 p.

- - - 1985, Consolidation of alluvial-fan deposits an engineering geologic hazard that affects Utah and the surrounding Basin and Range region: U.S. Soil Conservation Service unpublished report, 7 p.

- - - 1988, Field trip to assess accelerated bank erosion problem on Dry Gulch Creek, Uinta County, Utah: U.S. Conservation Service unpublished report, 4 p.

Rawson, R.R., 1957, Geology of the southern part of the Spanish Fork Peak quadrangle, Utah: Brigham Young University Research Studies, Geology Series, v. 4, no. 2, 33 p.

Rigby, J.K., 1962, Some geomorphic features of the southern Wasatch Mountains and adjacent areas: Brigham Young University Geology Studies, v. 9, part 1, p, 80-84.

Rodgers, J.L., 1977, Report and recommendations for selected individual wastewater disposal systems in the Roosevelt and Vernal areas, Duchesne and Uinta Counties, Utah : Utah Geological and Mineral Survey Report of Investigation 119, 16 p.

Rollins, Brown and Gunnell, Inc., 1969, Soils investigation, proposed Cornet Store, Cedar City, Utah: Unpublished consultant's report 6884, 5 p.

- - - 1973, Soils investigation Zions Bank, Hurricane Utah: Unpublished consultant's report 73147, 4 p.

- - - 1979, Soils and foundation investigation, Hurricane Seminary, Hurricane, Utah: Unpublished consultant's report 7902-1, 7 p.

- - - 1980a, Soils and foundation investigation Job Service building, Cedar City, Utah: Unpublished consultant's report 7901-156, 6 p.

- - - 1980b, Soils and foundation investigation, Cedar City K-Mart, Cedar City, Utah: Unpublished consultant's report 8001-2, 10 p.

- - - 1980c, Soils foundation investigation Sunrise Subdivision: Unpublished consultant's report, 5 p.

- - - 1981, Soil and foundation investigation Richfield community recreational facility, Richfield, Utah: Unpublished consultant's report, 8 p.

- - - 1982, Soil and foundation investigation Utah State liquor store, Cedar City, Utah: Unpublished consultant's report 8201-96, 7 p.

- - - 1984, Soil and foundation investigation, Fiddlers Canyon detention pond no. 1, Cedar City, Utah: Unpublished consultant's report 8401-151, 7 p.

- - - 1985, Soil foundation investigation Cedar City High School: Unpublished consultant's report 8501-070, 11 p.

Sack, Dorothy, 1988, Quaternary geology of Tule Valley west-central Utah: Utah Geological and Mineral Survey Map 124, 55 p., scale 1:100,000.

Stephens, J.C., and Sumsion, C.T., 1978, Hydrologic reconnaissance of the Dugway Valley - Government Creek area, west-central Utah: Utah Department of Natural Resources Technical Publication No. 59, 47 p.

Sweeting, M.M., 1972, Karst landforms: London, Macmillan, 362 p.

Thomson, Fred, 1965, Feasibility geology report Tawanta dam and Reservoir sites, Upalco Unit Central Utah Project, Utah: U.S. Bureau of Reclamation unpublished report G-221, 9 p.

Tourtelot, H.A., 1974, Geologic origin and distribution of swelling clays: Bulletin of the Association of Engineering Geologists, v. XI, no. 4, p. 259-275.

United States Bureau of Reclamation, 1985, SEED report on Causey Dam, upper Colorado Region, Weber Basin Project, Utah: U.S. Bureau of Reclamation unpublished report, variously paginated.

United States Forest Service, 1975, Land systems inventory for the Vernal, Flaming Gorge, Roosevelt, and Duchesne Ranger Districts, Ashley National Forest: U.S. Forest Service unpublished report, 3 volumes, variously paginated.

- - - 1976, Land systems inventory for the Vernal, Flaming Gorge, Roosevelt and Duchesne Ranger Districts, Ashley National Forest: U.S. Forest Service unpublished report, 3 volumes, variously paginated.

- - - 1981, Land systems inventory for the Vernal, Flaming Gorge, Roosevelt, and Duchesne Ranger Districts, Ashley National Forest: U.S. Forest Service unpublished report, 3 volumes, variously paginated.

- - - 1982, Land systems inventory for the Vernal, Flaming Gorge, Roosevelt and Duchesne Ranger District, Ashley National Forest: U.S. Forest Service unpublished report, 3 volumes, variously paginated.

Utah Department of Transportation, 1964, Comb Wash to Butler Wash; foundation report on Comb Wash bridge: Unpublished report, project S-0402(4), 2 p.

- - - 1966, Interim report on experimental test section over the Mancos Shale and final report on project SR-10 between Price and Huntington: Unpublished report, project no. F-024-2(5), 43 p.

Utah Department of Water Resources, 1981, Lower Fremont River development preliminary design investigation final report: Unpublished report comprising four supplemental reports, 70 p.

Utah Department of Water Resources and Palmer-Wilding Consulting, 1980, Lower Fremont River development, preliminary design investigation, FCRC no. 501-828-1116-1: Utah Division of Water Resources unpublished report, variously paginated.

Utah Power and Light Company, 1981, Subsidence monitoring program annual report for 1981, submitted to the U.S. Department of Interior, Office of Surface Mining Minerals Management Service: Utah Division of Oil Gas and Mining, variously paginated.

- - - 1987, Subsidence monitoring program, annual report for 1987 submitted to U.S. Department of Interior, Office of Surface Mining Minerals Management Service: Utah Division of Oil Gas and Mining, variously paginated.

Utah State Department of Highways, 1966, Materials inventory of Tooele County: Utah Department of Highways, 25 p.

Utah State Soil Conservation Commission and Schick International, 1976, Geology and sedimentation appendix, Richfield-West Sevier watershed flood prevention project: Unpublished report for Utah State Soil Conservation Commission, variously paginated.

Van, Heber, 1986, South Richfield to north Richfield; collapsible soil study near W.B. I-70, stations 1908+00: Unpublished Utah Department of Transportation memorandum, project No. I-70 (23) 36, 2 p.

Varnes, D. J., and Van Horne, Richard, 1984, Surficial geologic map of the Oak City area, Millard County, Utah: U. S. Geological Survey Open-File Report OF-84-115, scale 1:31,680.

Western Engineers, Inc., 1982, Geological and geotechnical report for the Monticello dam and reservoir: Unpublished consultant's report, 16 p.

Williams, E.J., 1970, Geomorphic features and history of the lower part of Logan Canyon, Utah: Utah Geological and Mineral Survey Bulletin 86, 167 p.

Wilson, J.R., 1976, Glaciated dolomite karst in the Bear River Range, Utah: Unpublished Ph.D. dissertation, University of Utah, 123 p.

Winans, A.R., 1985, Geologic investigation Grove Creek debris basin, Utah County, Utah: U.S. Soil Conservation Service unpublished report, 2 p.